INJECTION MOLDING OF GLASS FIBER REINFORCED POLYPROPYLENE COMPOSITE FOAMS WITH LAMINATE SKINS

P. Kasemphaibulsuk\textsuperscript{1}, M. Holzner\textsuperscript{2,3}, T. Kuboki\textsuperscript{1}, A. Hrymak\textsuperscript{4}

1. Department of Mechanical and Materials Engineering, University of Western Ontario, London, Ontario, Canada, N6A 5B9
2. Fraunhofer Project Centre for Composites Research, University of Western Ontario, London, Ontario, Canada, N6M 0E1
3. Fraunhofer Institute for Chemical Technology, Pfinztal, Germany, 76327
4. Department of Chemical and Biochemical Engineering, University of Western Ontario, London, Ontario, Canada, N6A 5B9

Abstract

Sandwich panels which consist of discontinuous glass fiber reinforced polypropylene composite foam core and continuous glass-fiber reinforced polypropylene laminate skins were manufactured using industry-scale equipment in a streamlined manner. The process included the two stages: (1) continuous glass-fiber reinforced polypropylene laminates as the face skins were produced using an automated tape layup machine and a hydraulic press and (2) discontinuous glass-fiber reinforced polypropylene composite as the core was foam injection-molded onto the face laminates (i.e., overmolding) with a physical blowing agent, nitrogen. The results suggested that the addition of the laminate skins and foaming by the core-back (or mold opening) technique can greatly reduce weight of material needed to have the same bending stiffness and maximum bending force.

Introduction

Fiber reinforced thermoplastic composite foams have recently received attention from transportation industries such as rail and automobile due to their high specific modulus and strength. Foam injection molding has been used to produce fiber reinforced thermoplastics foam products with three-dimensional, complex shapes. Advantages of foam injection molding are less material usage, weight reduction, and excellent dimensional stability (i.e., less shrinkage and warpage) \cite{1,2,3,4}.

Although fiber reinforced thermoplastic composite foams have been used for various parts, transportation industries seek materials that have higher specific modulus and strength, as well as faster-paced and further automated production technologies. One way to increase specific modulus and strength of fiber reinforced thermoplastic composite foams under flexural loading is to integrate them with another reinforcement material as the face skins, thus forming a sandwich structure. A continuous-fiber reinforced thermoplastic laminate is a candidate for the face skins because it has high specific modulus and strength \cite{5,6}. Two manufacturing routes have often been taken to bond a thermoplastic foam core and thermoplastic composite face skins: (i) compression molding of a stack of a pre-made thermoplastic foam core and pre-made thermoplastic composite face skins \cite{7,8} and (ii) joining of a pre-made thermoplastic foam core and premade thermoplastic composite face skins with an adhesive. Although sandwich panels can be manufactured successfully through the two manufacturing methods, it is preferable to streamline the manufacturing process in an industrial setting, especially the bonding process of a foam core and face skins.

In this study, fiber reinforced thermoplastic sandwich foam panels were manufactured using industry-scale equipment in a streamlined manner. Continuous-fiber reinforced thermoplastic laminates as the face skins were produced using an automated tape layup machine and a hydraulic press. The fiber reinforced thermoplastic composite core was foam injection-molded onto the face laminates (i.e., overmolding) with a physical blowing agent to manufacture panels with sandwich structures. In addition, effects of void fraction and configuration of skin laminates on the foam morphologies and mechanical properties of the sandwich foams were investigated.

Experimental Procedure

Materials and fabrication of sandwich panels

Discontinuous glass fiber reinforced polypropylene composite (Celstran® PP-GF 20-02, Celanese) was used as the core material of a sandwich panel. The composite had a density of 1.030 g/cm\textsuperscript{3} and glass fiber content of 20 wt%. The composite was supplied in the form of pellets which include fibers of about 10 mm in length. Continuous, unidirectional glass-fiber reinforced polypropylene tape (Celanstran® CFR-TP PP GF70-13, Celanese) was used as the laminate skins of a sandwich panel. The tape had a
density of 1.656 g/cm³ and glass fiber content of 70 wt%. The tape was supplied as roll of 75 mm in width and 0.25 mm in thickness.

Solid continuous-fiber composite laminates for sandwich skins were manufactured through two process steps: lay-up of the tapes and consolidation of the tape lay-up. Two types of stacking sequence of laminates, a quasi-isotropic lay-up with three layers of tapes [0/±60] and an orthotropic lay-up with two layers of tapes [0/90], were prepared for this study. Both laminates are asymmetrical, but a symmetric sandwich panel can be created when two same laminates are used as top and bottom skin layers. Tape lay-up was performed using an automated tape lay-up machine (RELAY® Station 1000, Fiberforge), which enables automated, rapid positioning, angle tape laying, and tape stacking. After the tape laying, the lay-ups were trimmed to have dimensions of 450 mm x 450 mm using a shear cutter.

In order to consolidate the tape lay-up to form one solid continuous-fiber composite laminate, the lay-up was placed between aluminum sheets (preheated at 240 °C) to secure it in place and allow it to be easily moved to and placed in the consolidation mold while the lay-up is in a melt state. The lay-up with the aluminum sheets was heated to 240 °C in a circulating hot air oven (Universal Oven, HK Präzisionstechnik) and then pressed using an industry-scale, 2,500-tonne hydraulic press (DCP-U 2500/2200, Diefenbacher). For the hydraulic press, the mold temperature was set to 55 °C, and the force applied was set to 900 kN for 45 seconds.

The discontinuous-fiber composite pellets were foam injection molded using an industry-scale, 1600-ton injection molding machine (KM 1600/12000/4300 MX L, KraussMaffei) with a MuCell® injection unit. The MuCell® process enables foaming with physical blowing agents such as nitrogen or carbon dioxide [9], [10]. In this study, the barrel and mold temperatures were fixed at 240 °C and 50 °C, respectively. Nitrogen was used as a physical blowing agent, and its content for the composite was fixed at 0.3 wt%.

In order to manufacture a sandwich panel, one laminate was attached to the core side of the mold while the other laminate was attached to the cavity side of the mold. A fan gate was used in this study, and the 0° fiber direction of the consolidated laminates matches the flow direction of composite melt from the fan gate.

The high-pressure foaming process was used to manufacture sandwich foam panels with various thicknesses by opening a core side of the mold. The high-pressure foaming offers more uniform cell distribution across the plaques than the low-pressure foaming process. An overall void fraction of a foamed specimen can be calculated using the following equation:

\[
V_f = \frac{d_a - d_b}{d_a}
\]  

where \(d_a\) and \(d_b\) are depth of mold cavity after and before the mold is opened, respectively. Sandwich foam panels with a void fraction (VF) of 9.1 %, 20.0 %, and 33.3 % were produced by increasing the depth of mold cavity, which corresponds to thickness of sandwich foam panels, from 4 mm (= \(d_b\)) to 4.4 mm, 5 mm, and 6 mm, respectively.

The density of a sandwich panel was calculated by measuring the weight of a 180 mm x 180 mm cut piece. Specimens for mechanical tests were cut from a panel with their length direction matching the flow direction of the composite melt from the fan gate as well as the 0° fiber direction of the consolidated tape laminates.

**Optical microscopy**

An optical microscope with reflected light (Eclipse L150, Nikon, Nikon) equipped with a digital camera (DXM1200, Nikon) was used to observe microstructure. The area of the gauge section was polished through the thickness and then examined. Micrographs taken at different areas were composed to cover a broad area of the specimen.

**Mechanical testing**

Flexural tests were performed on rectangular specimens with 80 mm in length and 10 mm in width as per ISO 178 standard, using a universal testing machine (Criterion® Model 45, MTS) with a load cell of 100 kN capacity. The crosshead speed was 2 mm/min and the span length was 40 mm. At least five specimens were tested for each sample.

**Results and Discussion**

**Density and cell morphology**

Figure 1 shows density of composites without laminate skins, composites with [0/±60] skins, and composites with [0/90] skins as a function of the void fraction. The results suggest that the density of all the composites decreased linearly as the void fraction increases. However, the densities of the sandwich composites with [0/±60] skins and [0/90] skins were always about 28% and 17% higher than those of the composites without laminate skins at a given void fraction, respectively.

Figure 2 shows optical micrographs of cross-sections of composites with a void fraction of 0 % (solid), 9.09, 20, and 33.3%. The vertical direction of the micrographs corresponds to the thickness direction of specimens. The foam composites without laminate skins have three distinct layers: (i) a foam composite core, where dark regions represent bubbles, and (ii) two solid composite skins. On the other hand, the foam composites with laminate skins include five layers: (i) a foam composite core, (ii) two solid
composite inner skins, and (iii) two solid laminate outer skins (each skin consists of [0/±60] layers or [0/90] layers). The figure also suggests that more bubbles nucleated and coalesced when void fraction was increased from 9.1 to 33.3\% for each laminate configuration (i.e., composites with and without laminate skins).

**Flexural properties**

Figure 3 charts typical stress-strain curves of composites without laminate skins (Figure 3a), composites with [0/90] skins (Figure 3b), and composites with [0/±60] skins (Figure 3c) from flexural tests. Four curves in each figure were obtained from composites with 0 (solid or unfoamed), 9.1, 20.0, and 33.3\% void fraction. For all the curves, the stress increased in an almost linear manner with the strain in the initial loading region. With a further increase in strain, the stress decreased sharply. The specimens were deformed further, beyond the maximum stress level and eventually fractured. The figure also shows that the initial curve slope (i.e., modulus) and maximum stress (i.e., strength) decreased with the increase of void fraction. It is noted that the maximum strain increased with the increase of void fraction for the composites with laminate skins (Figure 3b and Figure 3c), but that for the composites without laminate skins little changed (or slightly decreased) with the change in void fraction (Figure 3a). When the composites with different laminate configurations are compared, the composites with laminate skins performed better than those without laminate skins, but the composites with [0/±60] skins and [0/90] skins exhibited similar stress-strain curves at a given void fraction.

Figure 4 illustrates flexural strength of composites as a function of density. It can be seen that the strength of all the composites decreased linearly as the density decreased, but strength of the composites with laminate skins decreased more sharply with the decrease of density. Flexural strength was ranked in the following order at a given density: the composites with [0/90] skins ≥ the composites with [0/±60] skins > the composites without laminate skins.

Figure 5 depicts the flexural modulus of composites as a function of density. Similar to the strength results, the modulus of all the composites decreased linearly as the density decreased, but the modulus of the composites with laminate skins decreased more rapidly with the density decrease. The flexural modulus was ranked in the following order at a given density: the composites with [0/90] skins ≥ the composites with [0/±60] skins > the composites without laminate skins.

**Material selection**

Bending stiffness and maximum bending force are important design requirements for structural applications of a material. A sandwich panel is designed to give a structure with high bending stiffness and bending force at low weight. Material index can be used to rank materials which meet design requirements [11]. Material index is the property or a group of properties that maximizes performance for a given design. It provides criteria of excellence that allow ranking of materials by their ability to perform well in the given application.

Material index for a light, “strong” panel is expressed as follows [11]:

\[
M_{\text{Strong}} = \frac{\sigma_{f}^{1/2}}{\rho}
\]  

or the logarithmic form,

\[
\log \sigma_{f} = 2 \log \rho + 2 \log M_{\text{Strong}}
\]

The best materials for a light, strong panel are those with the greatest value of this material index. When data of composites manufactured in this study are plotted on the material property chart of \(\log \sigma_{f}\) versus \(\log \rho\) (Figure 6), composites on a line of slope 2 have the same value of the material index, \(M_{\text{Strong}}\), and perform equally well as a light, strong panel; those above the line are better; those below, worse. Therefore, a series of the lines can be a guideline for a light, strong panel, which allows us to rank materials: a material on a more left line has greater material index. The figure suggests that the top three materials are (1) the 20.0% VF composite with [0/90] skins, (2) the 33.3% VF composite with [0/90] skins, and (3) the 9.1% VF composite with [0/90] skins.

Material index for a light, “stiff” panel is expressed as follows [11]:

\[
M_{\text{Stiff}} = \frac{E^{1/3}}{\rho}
\]  

or the logarithmic form,

\[
\log E = 3 \log \rho + 3 \log M_{\text{Stiff}}
\]

When data of composites manufactured in this study are plotted on the material property chart of \(\log E\) versus \(\log \rho\) (Figure 7), composites on a line of slope 3 have the same value of the material index, \(M_{\text{Stiff}}\), and perform equally well as a light, stiff panel. The figure suggests that the top three materials are (1) the 33.3% VF composite with [0/90] skins, (2) the 20.0% VF composite with [0/90] skins, and (3) the 33.3% VF composite with [0±60] skins.

**Conclusions**

Sandwich panels with the glass fiber reinforced PP composite foam core and laminate skins were manufactured successfully using the industry-scale equipment in a streamlined manner. First, the face skins of
the sandwich panels were made of continuous-fiber reinforced PP laminates: unidirectional tapes were laid up using the automated tape layup machine, and the stacked tapes were consolidated using the oven and hydraulic press. Next, the discontinuous glass-fiber reinforced PP composite core was foam injection-molded between the face laminates (overmolding) with nitrogen, the physical blowing agent. The mechanical test results suggested that flexural modulus and strength of the composites decreased with the increase of void fraction, but increased by the addition of [0/90] or [0±60] laminate skins significantly. The material indices of the sandwich panels suggested that weight of material can be greatly reduced by adding laminate skins and increasing void fraction through the core-back (or mold opening) technique when the same bending stiffness and maximum bending force are required.

Acknowledgements

The authors are grateful for the financial support provided by Clean Rail Academic Grant Program of Transport Canada and the material supplied by Celanese Corporation. The composites work was performed at the Fraunhofer Project Centre (FPC) for Composites Research at the University of Western Ontario.

References

Figure 1 Density of sandwich panels versus void fraction.

<table>
<thead>
<tr>
<th>Volume fraction</th>
<th>No laminate skin</th>
<th>[0/90] skin</th>
<th>[0/-60] skin</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
<td><img src="image3" alt="Image" /></td>
</tr>
<tr>
<td>9.1%</td>
<td><img src="image4" alt="Image" /></td>
<td><img src="image5" alt="Image" /></td>
<td><img src="image6" alt="Image" /></td>
</tr>
<tr>
<td>20.0%</td>
<td><img src="image7" alt="Image" /></td>
<td><img src="image8" alt="Image" /></td>
<td><img src="image9" alt="Image" /></td>
</tr>
<tr>
<td>33.3%</td>
<td><img src="image10" alt="Image" /></td>
<td><img src="image11" alt="Image" /></td>
<td><img src="image12" alt="Image" /></td>
</tr>
</tbody>
</table>

Figure 2 Optical micrographs of cross-sections of sandwich panels.
Figure 3 Typical stress-strain curves of (a) composites without laminate skins, (b) composites with [0/90] skins, and (c) composites with [0/±60] skins.

Figure 4 Flexural strength of composites versus density.

Figure 5 Flexural modulus of composites versus density.

Figure 6 Flexural strength versus density.

Figure 7 Flexural modulus versus density.